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# Robustness analysis and Evaluation of a PMSG-based Marine Current Turbine System under Faulty Conditions

S. Toumi, S.E. Ben Elghali, M. Trabelsi, E. Elbouchikhi, M.E.H. Benbouzid, M.F. Mimouni

**Abstract**—This paper deals with a Permanent Magnet Synchronous Generator (PMSG) driven by a Marine Current Turbine (MCT) through a PWM power rectifier and used for isolated sites. The generator model is established in the synchronous rotating  $dq$  reference frame. The control of the speed, the  $d$ -axis current, and the  $q$ -axis current is achieved using PI correctors. Robustness and performance of the considered system are evaluated in healthy and faulty conditions. The faulty mode deals with the study of single and multiple open-switch damages appearing in the PWM power rectifier. Simulations are carried-out to highlight the proposed PMSG-based MCT performance in both cases.

**Index terms**—Marine current turbine, permanent magnet synchronous generator, PWM power rectifier, MPPT, control, open-circuit faults.

## NOMENCLATURE

MCT	=	Marine Current Turbine;
PMSG	=	Permanent Magnet Synchronous Generator;
MPPT	=	Maximum Power Point Tracking;
IGBT	=	Insulated Gate Bipolar Transistor;
PWM	=	Pulse Width Modulation;
$P_m$	=	Mechanic power;
$C_p$	=	Power coefficient;
$\lambda$	=	Tip speed ratio;
$\beta$	=	Blade pitch angle;
$\rho$	=	Fluid density;
$r$	=	Turbine radius;
$v_t$	=	Tidal speed;
$R_s$	=	Resistance.

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## I. INTRODUCTION

Because of oceans cover more than 70% of the earth, many new renewable energy sectors are emerging and interesting development are taking place such as thermal energy, wave energy and marine tidal energy [1]. Indeed, the potential of electric power generation from marine tidal currents is very interesting; it has been shown that 48% of the European tidal resource in the UK, 42% in France and 8% in Ireland [2] [3].

Unfortunately, in the literature there is no study about defaults in the hydraulic conversion chain. But, certainly, hydrodynamic energy conversion systems are exposed to environmental and functional constraints. Firstly, environmental constraints are due to the severe weather conditions because of the geographic location (installation under the sea and existence of harmonic current speeds caused by the swell and wave), second, functional constraints are due to the increase in power implies to a higher voltages and / or currents transited. These constraints provide the degradation of performance of the various functional blocks of the system and its accelerated aging process, which leading to many faults essentially related to the blades, to the PMSG (short-circuit between turns, between phases and between phase and neutral) and even to the rectifier (short-circuit faults, open-circuit faults and intermittent gate misfiring faults).

This paper describes the hydrodynamic conversion system by giving the modeling of each component: the MCT, the PMSG and the PWM power rectifier. The control of this chain is achieved by using: MPPT control for extracting of the maximum power and proportional integral correctors to control the speed and the  $dq$ -axis currents. Besides, we are focus on the impact of an open-circuit fault in the PWM power rectifier.

This paper is structured as follows; in section II, the hydrodynamic conversion chain structure is given. In section III, the models of the marine current turbine and the PMSG are developed. In section IV, control of the system will be presented. In section V, performance evaluation results are presented. The conclusion is given in section VI.

## II. HYDRODYNAMIC CONVERSION CHAIN STRUCTURE

As shown in fig. 1, the conversion chain is composed by marine turbine, a permanent magnet synchronous machine coupled to a DC Bus through a PWM power rectifier.

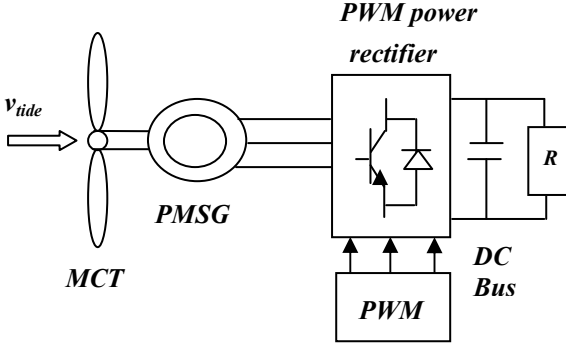


Fig. 1. General scheme for a hydraulic conversion chain in isolated site

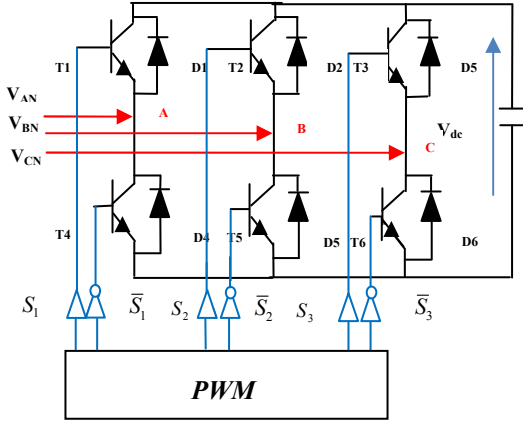


Fig. 2. PWM power rectifier topology

Fig. 2 presented the PWM power rectifier, this converter uses the three-phase voltage sources provided by the PMSG. It composed by a three legs, each leg features two semiconductor switches ( $T_k, T_{k+3}$   $k=1, 2, 3$ ) with antiparallel connected freewheeling diodes ( $D_k, D_{k+3}$ ). The switches of the same leg are controlled by a PWM bloc in the form of a logic control signals  $S_k$  ( $k = 1, 2, 3$ ) also known gate signals, it defined by:

$$S_k = \begin{cases} 1 & \text{if } T_k \text{ on and } T_{k+3} \text{ off} \\ 0 & \text{if } T_{k+3} \text{ on and } T_k \text{ off} \end{cases} \quad (1)$$

### III. ENERGY CONVERSION SYSTEM MODELING

#### A. Marine current turbine modeling

The mechanic power for a marine current turbine has a similar dependence to that of a wind turbine and is given by the following equation [4] [5]:

$$P_m = \frac{1}{2} C_p (\lambda, \beta) \rho \pi r^2 v_t^3 \quad (2)$$

$C_p$  presents the percentage of mechanical power that can be extracted from the fluid stream by the turbine.

For typical MCTs, the optimal  $C_p$  value for normal operation is estimated to be in the range of

0.35-0.5 [6]. Indeed, basing on the experimental results and for a given turbine, the  $C_p$  can be approximated as a function of the tip speed ratio  $\lambda$  and the blade pitch angle  $\beta$  [7].

Fig. 3 illustrates the  $C_p$  curve for simulations.

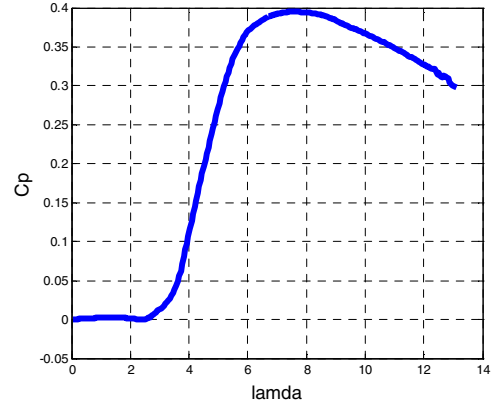


Fig. 3. Power Coefficient curve  $C_p$

#### B. Marine current generator modeling

The generator chosen for the marine current system was the PMSG [8], it has been chosen because of its advantages such as high efficiency, compact structure and the possibility to eliminate the gearbox that reduce the maintenance and this very favorable in terms of underwater application [9].

Dynamic modeling of PMSG can be described in d-q reference system as follows [10] [11] [12]:

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{R_s}{l_s} i_{sd} + p\Omega i_{sq} + \frac{v_{sd}}{l_s} \\ \frac{di_{sq}}{dt} = -\frac{R_s}{l_s} i_{sq} - p\Omega i_{sd} - \frac{p\Phi_a}{l_s} \Omega + \frac{v_{sq}}{l_s} \\ \frac{dw}{dt} = \frac{p}{J_t} T_m - \frac{p}{J_t} T_{em} - \frac{p}{J_t} f\Omega \\ T_{em} = \frac{3}{2} p\Phi_a i_{sq} \end{cases} \quad (3)$$

### IV. ENERGY CONVERSION SYSTEM CONTROL

Fig. 4 shows the control scheme for the energy conversion chain.

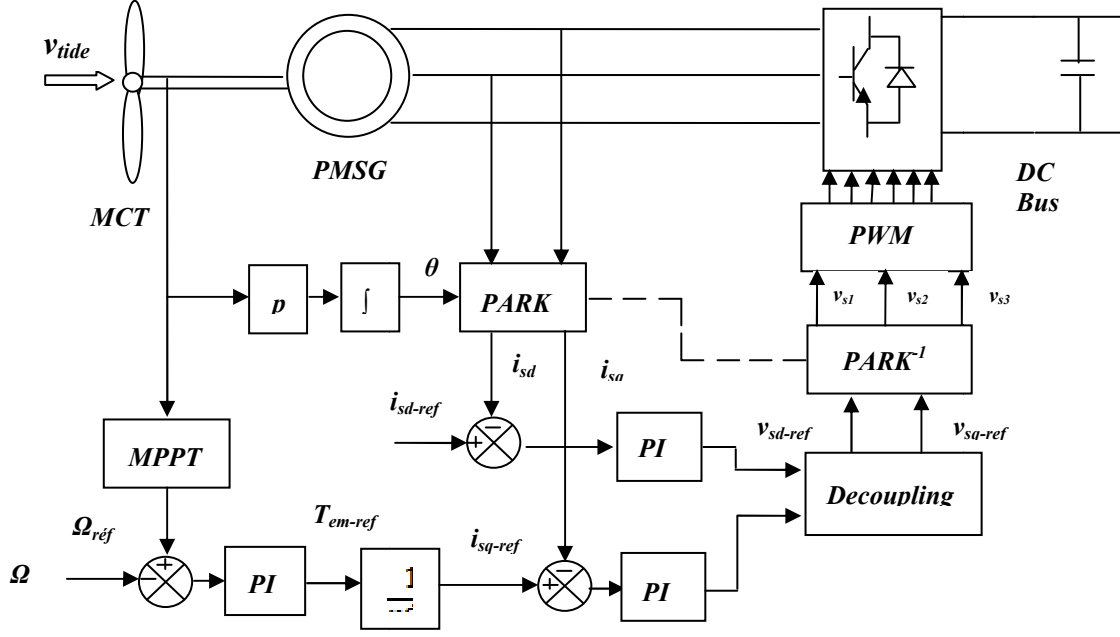


Fig. 4. Control scheme of energy conversion chain

Firstly, MPPT technique consists in controlling the rotor speed to keep the turbine tip ratio  $\lambda$  at its optimal value, thus keeping the turbine power coefficient  $C_p$  at the maximum value, which leads to achieve the expected power extracted by the MCT.

The expression of the turbine speed reference calculated by the conventional MPPT is given by:

$$\Omega_{ref} = \frac{v_m \lambda_{opt}}{r} \quad (4)$$

Then, a classical speed control of the generator ensures the convergences of the rotor speed to  $\Omega_{ref}$  based on PI control.

The d-axis current reference is set to zero to minimize resistive losses and therefore minimize current for a given torque, so, we can control the generator torque directly by the quadrature current component [13]. The q-axis current reference is calculated by the speed loop controller.

The required d-q components of the rectifier voltage vector are derived from two PI currents controllers. Then, we added the compensation terms to improve the dynamic response [14] [15].

Finally, PWM is used to generate the control signal to implement the vector control for the generator.

## V. PERFORMANCE EVALUATION RESULTS

### A. Simulation parameters

Tidal currents are proven by the effect of the moon. Indeed, the moon gravitational pull forces the ocean to bulge outwards on opposite sides of the earth, which causes a rise in the water level in places that are aligned with the moon and a decrease in water levels halfway between those two places. This rise in water level is accompanied by a horizontal movement of water called the tidal current.

Fig. 5 shows the simulation curve of marine current speed.

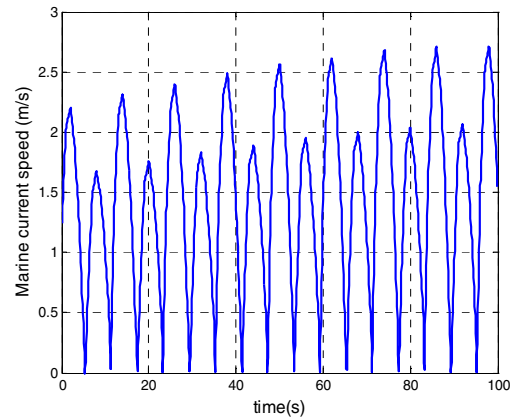


Fig. 5. Marine current speed

TABLE I. SYSTEM PARAMETER LIST

MCT PARAMETER	
Turbine blade radius	0.87 m
Number of blades	3
Fluid density	1027.68 Kg/m <sup>3</sup>
PMSG PARAMETER	
Generator stator resistance	0.173 mΩ
Generator d-axis reference	0.085 mH
Generator q-axis reference	0.951 mH
Permanent magnet flux	0.112 Wb
Generator inertia	0.0048 kg.m <sup>2</sup>
Viscosity coefficient	8.5 10 <sup>-3</sup> Nm/s
PWM POWER RECTIFIER	
Turn-On time	0.13 μs
Turn-Off time	0.445 μs
Dead time	4 μs
Duty-cycle frequency	5 kHz
DC-bus voltage	600 V

### B. Considered faults

Although IGBTs are rugged, they suffer failure due to excess thermal and electrical stress, these failures can be broadly categorized as short-circuit faults, open-circuit faults and intermittent gate misfiring faults. Indeed, IGBT's open-circuit faults are usually linked to the loss of bonding wires of the control signal or to a short-circuit fault causing rupture of the transistor [16] [17]. Also, this fault can arise when the switches are destructed by an accidental over current or a fuse connected with series for short protection is blown out [18]. Because of the open-circuit faults, the converter cannot synthesize desired output voltages and it provides a large torque ripple, an increased harmonic component in current [19].

In this section, we will consider an open circuit of the upper switch, the lower switch and the two switches on the same time of the first PWM power rectifier leg and we will consist in studying the influence of this fault on the PMSG phase currents.

Fig. 6 shows the three case of an open circuit.

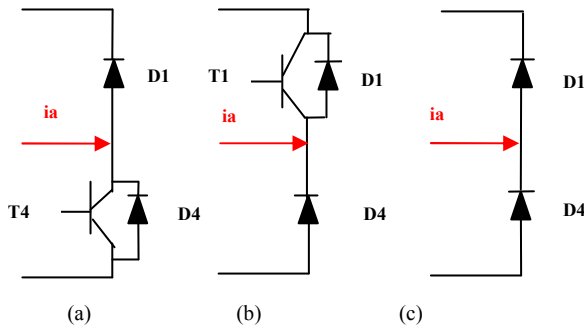


Fig. 6. (a) An open circuit of the upper switch (T1), (b) An open circuit of the lower switch (T4), (c) A simultaneous open-switches (T1 and T4)

### C. Simulation results

In this section, a simulation software has been set up by using the Matlab/Simulink/SimPowerSystem environment.

The parameters used in simulation tests are displayed in Table I.

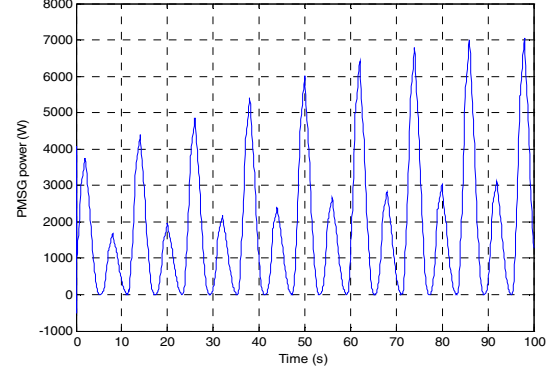


Fig. 7. PMSG power

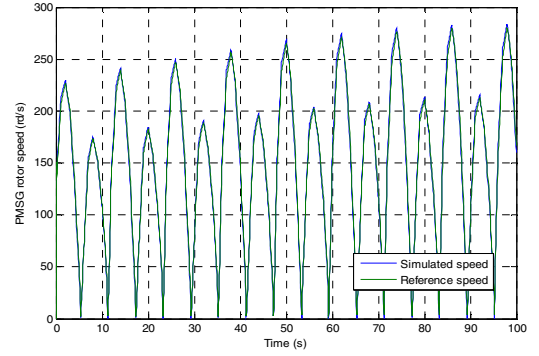


Fig. 8. PMSG speed and its reference

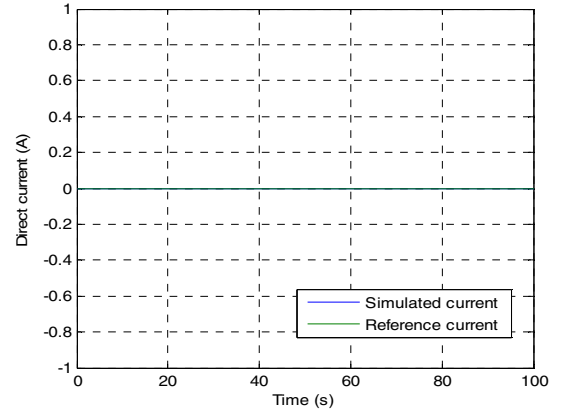


Fig. 9. Direct current and its reference

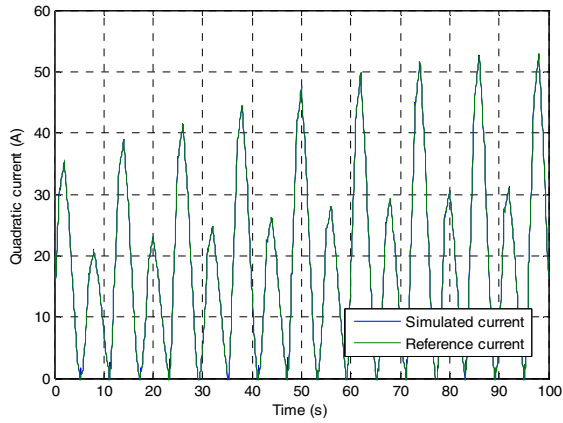


Fig. 10. Quadratic current and its reference

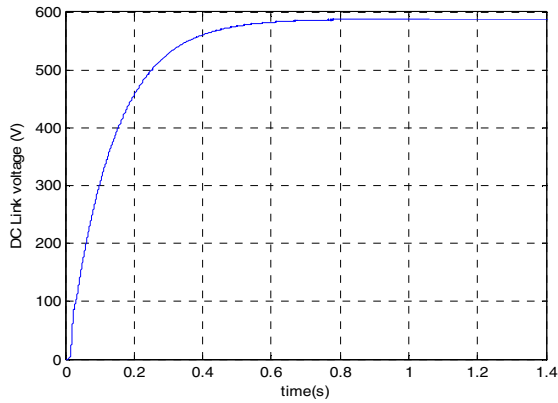


Fig. 11. DC link voltage

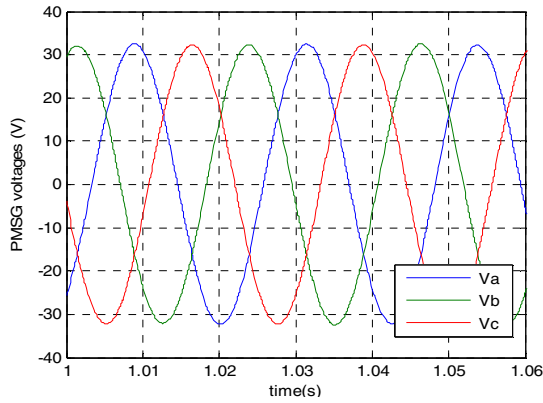


Fig. 12. PMSG voltages Vabc

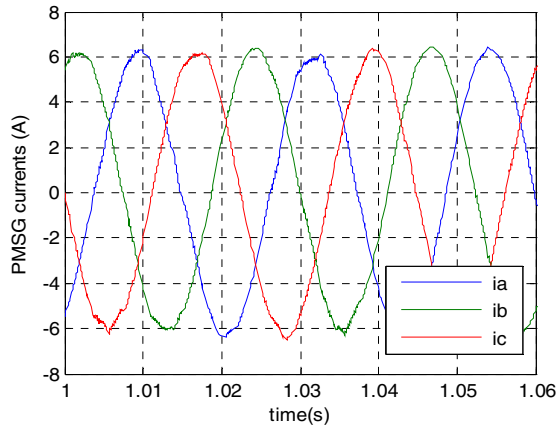


Fig. 13. PMSG currents iabc

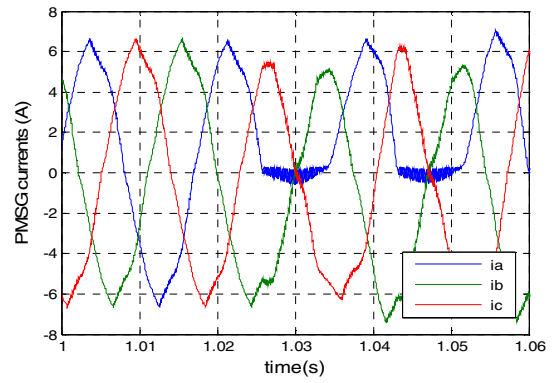


Fig. 14. PMSG currents iabc after an open-circuit fault in the upper transistor T1

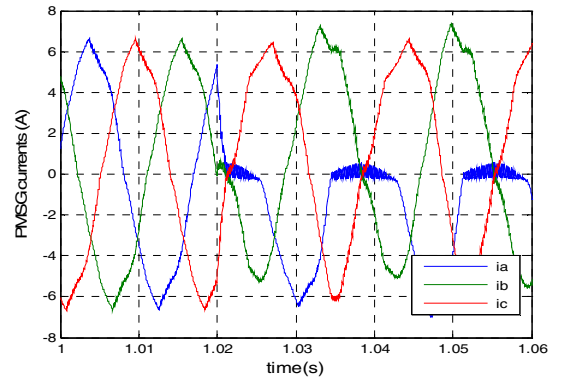


Fig. 15. PMSG currents iabc after an open-circuit fault in the lower transistor T4

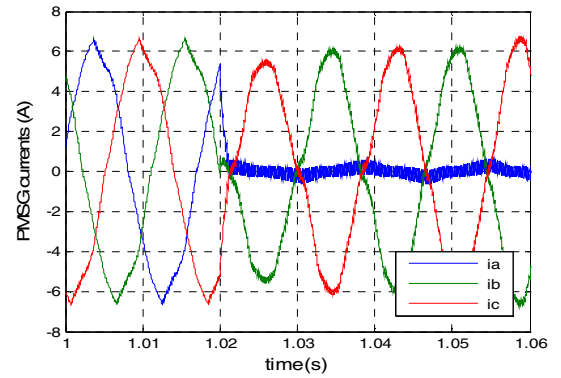


Fig. 16. PMSG currents iabc after a simultaneous open-switches (T1 and T4)

The PMSG power (fig. 7) and the PMSG speed (fig. 8) are deeply correlated with the current marine speed (fig. 5).

The direct current is maintained to zero (fig. 9), the quadratic current (fig. 10) and The PMSG rotor speed (fig.8) are maintained to theirs references. Thus proves the effectiveness of the established regulators.

Fig. 11 shows that the DC bus voltage is constant.

The PMSG voltages and currents are given by fig. 12 and fig. 13; they are three sinusoidal voltages and currents with constant frequency equal to 50Hz.

Under normal operating conditions and for faulty states, the PWM power rectifier has been modeled with a real model of the power switches and the by-pass diodes. A dead time of 4  $\mu$ s has introduced to prevent short-circuits within the rectifier legs. A fault condition is caused at  $t = 1.02$ s. In fig. 14, the fault is applied to the upper switch (T1), it is observed that the phase current  $i_a$  lost its negative direction and it is flowing only in a positive direction but in fig. 15, where the fault is applied to the lower switch (T4), we show the opposite result because in this case the phase current  $i_a$  lost its positive direction and conserve only its negative direction. In fig. 16, where we applied a multiple open-circuit fault for the upper switch (T1) and the lower switch (T4), the phase current  $i_a$  drops to zero.

## VI. CONCLUSION

This paper presents the modeling and the control of an energy conversion chain in isolated site based on a permanent magnet synchronous generator. We have used the d-q rotor reference to model overall the system. The main focus has been the study of the performance of the considered system in healthy and faulty conditions such as an open-circuit fault of a single and a multiple switch in the PWM power rectifier and its influence on the three phase currents. The proposed system has been performed by using Matlab/Simulink.

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